MOTION TRAJECTORIES FOR WIDE-AREA SURVEYING WITH A ROVER-BASED DISTRIBUTED SPECTROMETER

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ABSTRACT

A mobile ground survey application that employs remote sensing as a primary means of area coverage is highlighted. It is distinguished from mobile robotic area coverage problems that employ contact or proximity-based sensing. The focus is on a specific concept for performing mobile surveys in search of biogenic gases on planetary surfaces using a distributed spectrometer — a rover-based instrument designed for wide measurement coverage of promising search areas. Navigation algorithms for executing circular and spiral survey trajectories are presented for wide-area distributed spectroscopy and evaluated based on area covered and distance traveled.

KEYWORDS: mobile robot, mobile surveying, distributed spectrometer, Mars, search trajectory.

1. INTRODUCTION

Detection of signatures that indicate the existence of biomarkers is pertinent to astrobiology investigations on Mars and to the eventual establishment of a human presence there. Space agencies send landers and rovers to regions on the planet surface, where biomarker detection is likely, to conduct surveys in search of them. At Mars, deposits of surface and buried ice emit water vapor into the atmosphere through sublimation or evaporation. A number of models that contribute to our understanding of the exchange between the surface and atmosphere have been postulated. One representative model suggests that a short-term water reservoir, possibly manifested as adsorbed regolith water, actively interacts with the atmosphere at present [1]. Regions of high subsurface water content are thought to migrate through the regolith to the surface where the water vapor concentration would be relatively concentrated for a brief time before being quickly dispersed homogeneously into the atmosphere. While the NASA Mars Exploration Rovers [2, 3] have returned conclusive evidence that liquid water once flowed on the surface at their respective Martian landing sites, those rovers do not have instrumentation to detect water vapor or other biogenic gases. NASA and European Space Agency spacecraft in Mars orbit have also contributed to answering questions about the water story on Mars. Recent suggestions that localized sources of methane may be emanating from the Martian surface in present time [4] are particularly exciting since methane can be of biogenic (as well as other) origin. High-density concentrations of water vapor, methane, and other biogenic gases can be detected in the near-surface atmosphere by absorption spectroscopy.

As a robotics application, we are developing an effective concept for performing mobile science surveys on planetary surfaces using a distributed spectrometer instrument system that employs a rover to achieve wide measurement coverage of a promising search area [5]. The general problem is: directed wide-area survey and detection of biogenic gases (water vapor, methane, and others) in the ground-level atmosphere of Mars that may serve as indicators of past/present life. This paper addresses aspects of the mobility and navigation problem associated with the mobile surveying functionality of the instrument system. In the following sections, we describe baseline rover search and survey trajectories amenable to our distributed spectrometer configuration currently under development as part of a larger research effort.

2. DISTRIBUTED SPECTROMETER CONFIGURATION

The science instrument system is a variable path-length absorption spectrometer with components distributed as payloads mounted on a rover and on a post that is either fixed to a lander or emplaced on the terrain. A passive retroreflector is rigidly attached on top of the post, which remains stationary at a position central to a survey area. The rover will have near-infrared diode lasers tuned to absorption frequencies of biomarker gases and co-located laser radiation detectors. It will use a pan-tilt mechanism to aim laser beams at the passive retroreflector, which will reflect the incident laser light back towards the rover where its intensity can be measured by the detector array, thus establishing a beam path length that is twice the distance between the spectrometer and retroreflector. The spectrometer will detect the presence and concentration of biogenic gases crossing the laser beam. A 360° passive prism retroreflector (such as those commonly used with theolodite systems by civil engineers for land surveys) will be employed so that the rover can acquire such measurements from any radial line-of-sight direction.

The concept is illustrated in Fig. 1. A laser beam is depicted as a line representing emission/return of light from/to the spectrometer on the rover mast, and the retroreflector it is aimed at is barely visible in the far distance. Biogenic gas depicted as white lines of "vapor" emanating from the surface would be detected by partially absorbing the laser beam during a subsequent measurement after the rover takes its next steps along a survey trajectory in the direction it is currently heading.

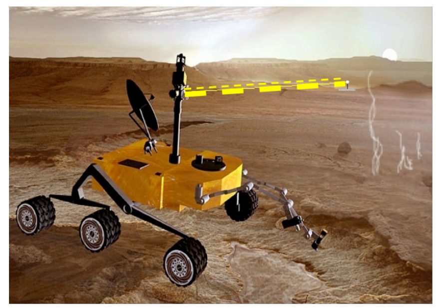

Figure 1. Distributed spectroscopy.

Obstructions such as boulders and rover-size scale variations in terrain relief will undoubtedly interrupt the line-of-sight from time to time. Because of this (and for initial establishment of spectrometer beam alignment), an acquisition sequence is used [6] in which a passive or active target close to the retroreflector is used to facilitate its recognition. The rover would then use a vision system to locate the target, process its images to determine deviation from ideal spectrometer beam alignment, and use that estimate to achieve finer alignment. The target would be constructed such that extraction of retroreflector distance would be computationally simple (or range would be a byproduct of the vision system if stereo correlation is feasible at the distance in question).

Accurate rover pose (position and orientation) estimation is important for mobile survey trajectory following and also for accurate measurements. Measurement sensitivity of absorption spectra depends on the laser beam path length and increases with the distance between the laser source and detector increases, making the technique suitable for scanning large areas relatively quickly. Sensitivity is adjusted by changing the distance (beam path length) between rover and retroreflector; alternative instruments that use compact multi-path spectrometers are limited by fixed path lengths. Accurate spectroscopy is a function of range measurement accuracy between the instrument and retroreflector. The instrument configuration facilitates rover pose estimation and path length measurement relative to the retroreflector given an accurate ranging capability.

3. MOBILE SURVEYING

For effective wide-area search of biogenic gases the distributed spectrometer requires surface navigation and surveying capabilities. During surveys the rover must handle challenges including executing an effective search trajectory, avoiding non-traversable surface hazards and recovering the trajectory afterwards, dealing with laser beam interruption by terrain obstructions during measurements, and localizing gas sources upon detection of highly concentrated signals. Capabilities to execute various motion behaviors and to transition between them in response to appropriate sensor events are required. Herein, we present algorithms that address search trajectory following only, as part of a behavior-based navigation approach to achieve the required instrument mobility. The basic concept underlying behavior-based motion control systems is that gross navigation tasks can be achieved using a set of special-purpose behaviors that perform distinct sub-tasks. Coordination or alternate activation of behaviors results in more intelligent, task-directed behavior suitable for autonomous navigation functions. Coordinated survey and obstacle avoidance behaviors are applied to achieve the required directed survey functionality.

3.1 Core Behaviors

The core behavioral functionalities considered for this system are hazard avoidance, traversal of effective survey trajectories, and localization of a detected biogenic gas source. In tandem, survey and obstacle avoidance behaviors permit intelligent reactions to mobility hazards and navigation contingencies while traversing survey trajectories between measurements. The rover will have to sometimes deviate from its survey trajectory in order to avoid terrain hazards. At other times, the rover survey trajectory may be blocked by a dead-end requiring it to backtrack and recover to resume the search. Fusion of behaviors is necessary for hazard-free trajectory following and particularly for dealing with trajectory recovery after avoiding isolated and extended obstacles. For basic hazard avoidance, we adopt existing reactive and/or deliberative algorithms. Currently, reactive trajectory recovery based on rover position knowledge is used and is built into circular and spiral survey algorithms appropriate for the instrument system configuration described in the next Section.

When an area of high biogas concentration is detected during a survey, its source can be localized as a result of rover motion towards the retroreflector along the azimuth at which it was detected. The spectrometer is being designed to maintain sensitivity to detectable biogases at laser-retroreflector separation distances as short as one meter. As such, the source of detected biogenic gas could be localized within considerable accuracy. Furthermore, wide-area surveys are feasible with the distributed spectrometer because its laser-retroreflector separation distances can be as far as hundreds of meters, and as mentioned above, its sensitivity increases with distance. Once a biogenic gas source is found, its location must be either recorded or marked to complete the localization task. If absolute position data are available, simple recording of the coordinates would be sufficient; otherwise, the location could be marked by passive or active markers (e.g., RFID devices [7]), carried by the rover during its search and deployed near the localized source.

3.2 Remote Sensor-Based Surveying

The objective is to provide a capability for systematic surveys by executing search patterns to achieve coverage of accessible terrain regions. By virtue of its open-path configuration, the distributed spectrometer is a *remote sensing* instrument system. As such, area coverage can be achieved without the need for the rover motion trajectories to physically cover the survey area. We will refer to methods for which this is the case as *remote sensor-based area coverage* methods. Measurements along a line-of-sight between the rover-mounted laser emitter/detector and the distant retroreflector account for coverage of terrain below that line-of-sight. This is a key advantage of the open-path measurement configuration that permits a 2-D search over terrain using discrete linear measurements from a distance (similar to scanning laser rangefinders). This is expected to yield significant increases in efficiency beyond what is possible for rover-based surveying using existing multi-path-length spectrometer designs (which use mirrors within the instrument enclosure to achieve long paths via multiple reflections) for which the measurement region is restricted to a localized area in front of the instrument. The method also has coverage advantages over rover-based surveying using point reflectance spectrometers for remote sensing in which each measurement is limited to a distant spot on the terrain, revealing nothing about the terrain between the spot and the instrument. The distributed open-path configuration will enable more efficient spatial coverage than conventional in-situ survey approaches.

Remote sensor-based area coverage contrasts with more common area coverage problems for mobile robotic surveys that employ sensing devices that require close proximity to or contact with the measured phenomenon (e.g., ground penetrating radar [8], humanitarian de-mining with metal detectors [9], fluorescence imaging for organic molecule detection [10]). For those applications, the robot mobility system must physically cover most, if not all, of the terrain in the survey area. We will refer to methods for which this is the case as *contact-based area coverage* methods. Of course, remote sensor-based methods are not applicable to all survey problems. For problems in which they are not a better solution, they are often excellent complements to contact-based methods, serving as an efficient means to survey wide areas and find local areas at which contact-based surveys should be done. Algorithms such as parallel line or parallel swath sweeps are commonly used to address such contact-based area coverage problems [11]. For our application, circular and spiral surveys are approaches that best account for and exploit the distributed measurement coupling between the rover and retroreflector. The underlying navigation technology needed to accomplish contact-based and remote sensor-based area coverage is more or less common to both tasks and is reasonably mature. However, the survey technology that would build on that underlying technology to achieve remote sensing surveys is not. This work represents some of the necessary development in the area of remote sensor-based area coverage.

4. SURVEY TRAJECTORIES

Rover survey trajectories are centered on the location of the stationary retroreflector. For the associated scientific exploration scenario, open-path absorption spectrometer measurements would be acquired at discrete locations along the survey trajectory to achieve area coverage. Circular or spiral survey/search trajectories are among the best candidates for our distributed spectrometer system configuration and measurement task. This is true when one considers completeness of area coverage by remote sensing and efficient use of rover resources (e.g., required energy for rover movements, traverse distance, etc) [12-14]. Mobile surveying algorithms for executing these candidate trajectory types are described next.

4.1 Concentric Circular Survey Trajectory Following

Beginning at a designated radial distance from the retroreflector, concentric circular trajectories of increasing radii can be followed to cover a designated *survey region*. While following a trajectory, the rover would move in arc-increments stopping periodically on the trajectory to acquire measurements along a ray between the rover-mounted laser bore-sight and the stationary retroreflector. By acquiring many measurements from different radial positions and distances, the rover samples the survey region in a discrete manner. We will refer to locations along a trajectory at which measurements should be acquired as *measurement nodes*.

The rover follows circular trajectories by incrementally traversing small arcs (between measurement nodes) at fixed radii of curvature for a single revolution, stopping at measurement nodes separated by arc length, s. Transitions from circular trajectories of radius ρ_i to a next trajectory of radius $\rho_{i+1} > \rho_i$ are made by executing straight-line motion in a radial direction from trajectory i to trajectory $i+1$ for a distance δ_c, a fixed separation distance between concentric circular trajectories. The process and parameters (ρ, δ, s) are depicted graphically in the left of Fig. 2; it continues until the n^{th} trajectory (encompassing the survey region) is followed or until a positive detection of biogenic gas in the measured spectrum is made. Black dots in the figure represent measurement nodes. The process is similar for spiral trajectories to be discussed below.

The location of the retroreflector is considered to be the origin of an inertial coordinate system in which the survey region and task is defined. This survey coordinate system is oriented such that its ground-plane coordinate axes are aligned with true north and east. Rover pose during surveys is relative to this coordinate system.

The trajectory following algorithm must account for an ability to maneuver the rover onto the trajectory from an arbitrary pose. This applies in two obvious cases: at the start of a survey and when recovering from hazard avoidance maneuvers that cause the rover to deviate from the trajectory. A less obvious case is when substantial accumulated position error is corrected by localization activities and true rover position is displaced from the trajectory; the same recovery approach can be used in each case. When the rover begins a concentric circular search from a position on the first concentric circle, it is only necessary to orient along a heading tangent to that circle and commence to survey. When it starts or resumes from an off-trajectory position it must determine a close, free-space point (x_c, y_c) on the trajectory and navigate to it. This point can be taken to be at a distance from the rover to the trajectory, along a ray from the survey coordinate system origin through the rover position. From any such rover position, Cartesian (x_r, y_r) or polar (d_r, θ_r), the ray through the origin is along the azimuth $\theta_r = \tan^{-1}(y_r/x_r)$, and the rover needs to orient along θ_r and drive to (x_c, y_c) on the trajectory (or to distance $d_r = \rho$ from the origin). If the rover is outside the concentric circle of radius ρ that it must drive to, it must orient along θ_r toward the origin and drive inward for a distance, $(d_r - \rho)$; if inside that circle, it must orient away from the origin along θ_r and drive outward for a distance, $(\rho - d_r)$. Here, d_r is rover distance from the origin, derived from range between the spectrometer and retroreflector as measured by the instrument. This measurement also facilitates recovery of spiral trajectory following.

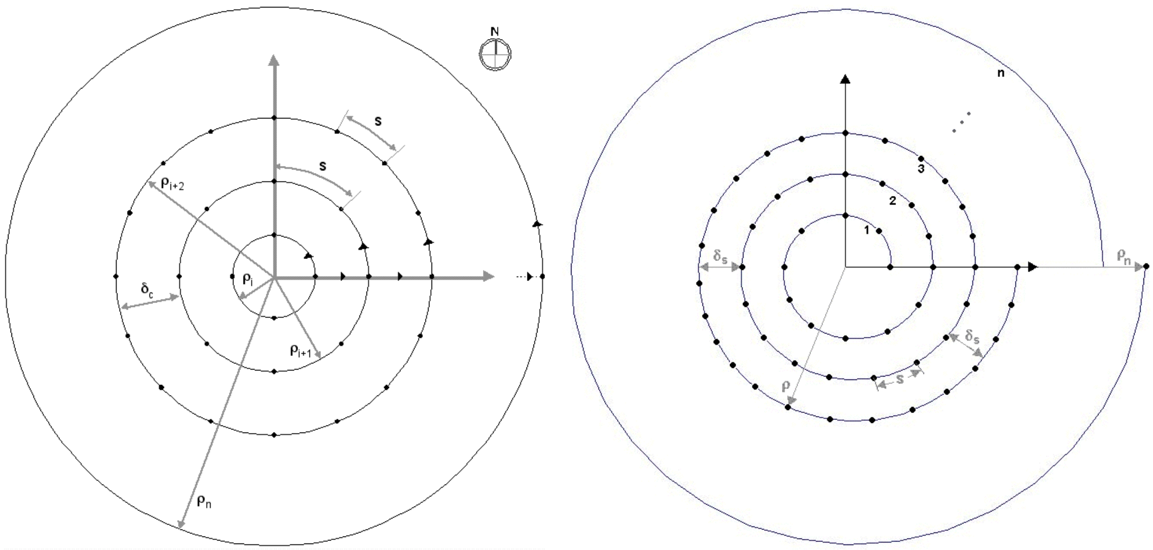

Figure 2. Trajectories and parameters for concentric circular (left) and spiral surveys (right).

4.2 Spiral Survey Trajectory Following

Beginning at a designated radial distance from the retroreflector, spiral trajectories of increasing radii can also be followed to cover a designated survey region. As is the case for circular trajectories, the rover would stop periodically at measurement nodes separated by fixed arc-increments, *s*, along the trajectory to acquire discrete near-surface atmospheric measurements throughout the region. A similar, but contact-based, coverage approach was proposed for mining regolith on the lunar surface by a mobile vehicle as part of a so-called spiral mining system [15].

For this application, we concentrate on linear spirals as survey trajectories that spiral outward from a given initial radius, ρ_I. For linear spirals, the radius ρ of the trajectory continually and gradually increases with distance traveled such that every 2π radians, consecutive arcs or branches of the spiral are separated by a fixed distance, δ_s; that is, (in polar coordinates) the radius increases linearly with the number of radians of the spiral. Equations for the linear spiral trajectory can be expressed in polar form as $\rho(\theta) = k\theta$, or in Cartesian form as $x(\theta) = k\theta \cos\theta$ and $y(\theta) = k\theta \sin\theta$, where θ increases monotonically and k is a constant. For a desired separation distance, δ_s, between each successive spiral branch it can be shown that $k = \delta_s/2\pi$.

Since the radius continually increases, transitions to successive branches of the spiral at larger radii are a byproduct of the trajectory itself and do not require specific maneuvers. This process is depicted graphically in the right of Fig. 2, with spiral branches labeled 1, 2, 3, … n; it continues until the n^{th} branch of the spiral trajectory is completed (thus encompassing the survey region) or until a positive detection of biogas in the measured spectrum is made.

For spirals, maneuvering onto the trajectory at the start of a survey or after deviating from it to avoid a hazard is facilitated by range and heading measurements to the retroreflector from which polar coordinates of the rover in the survey coordinate system can be determined. A close, free-space trajectory coordinate can be reached from off-trajectory by traversing inward or outward as necessary along the retroreflector-laser ray to the proper range or spiral radius, ρ.

Note that for contact-based area coverage, the spiral separation distance is typically the rover width so that its wheels (or short-horizon survey sensors) would necessarily cover all terrain in the survey region. With a remote sensor such as the open-path spectrometer such constraints can be relaxed and a given survey region can be scanned in less time, expending less energy.

For both algorithms, all parameters (ρ, δ, s, n) are configurable to allow flexibility in survey resolution and area coverage; they are constrained by rover kinematic limitations, maximum range of the open-path spectrometer, and terrain topography in the survey region.

4.3 Expected Coverage Performance

Selection of a candidate survey trajectory type can be based on metrics that provide some measure of relative resource usage during trajectory following in relation to the amount of area covered. Prior related distributed spectroscopy research considered a two-robot system in which one robot carried tunable diode lasers and the other carried the spectrometer's detector. The robots would cooperatively conduct remote sensor-based surveys. Parallel swath and circular search patterns performed with that configuration were compared analytically using a metric referred to as *quality of performance*, defined as a ratio of area covered to distance traveled [16]. Since both robots are mobile in that configuration, the search patterns are not directly applicable here; however, the performance metric can be applied. Similar measures, percent of area covered and distance traveled, were used to formulate metrics for single-robot, contact-based area coverage tasks [13]. Another study applied an energy efficiency metric, defined as a ratio of area covered to energy consumed, to evaluate parallel line, circular spiral, and square spiral trajectories [12]. Energy consumed by robot wheel motors was considered based on an empirically derived model of DC motors. The study revealed that circular spiral searches were most efficient for larger survey areas while parallel line scans were most efficient for small survey areas. Differences in energy efficiency were attributed in part to the number of turns required to follow the search pattern. We adopt the quality of performance metric as a preliminary basis for comparing expected performance of circular and spiral survey trajectories.

The survey area, A, covered by either a concentric circular or linear spiral trajectory is roughly the same and equal to $\pi\rho_n^2$, where ρ_n is the outermost circle or spiral branch radius. Surface areas occupied by a lander or retroreflector at the survey coordinate system origin and/or obstacles can be neglected without loss of generality for this comparison. As such, their qualities of performance are distinguished by distance traveled. The total traverse distance D_c required for a concentric circular survey is the sum of distances traveled on each circumference and the separation distances, δ_c, between them:

$$D_c = 2\pi\left(\sum_{i=1}^{n}\rho_i\right) + (n-1)\delta_c \tag{1}$$

For each linear spiral branch traversed (every $\theta = 2\pi$ radians), the spiral radius ρ increases by δ_s (Fig. 2), i.e., $\rho = (\delta_s/2\pi)\theta$. It can be shown [12] that the total traverse distance D_s required for a linear spiral trajectory is then expressed as

$$D_s = \frac{\delta_s}{4\pi}\theta_n^2 \tag{2}$$

where θ_n is the maximum spiral angle reached. If the spiral begins and ends as shown in Fig. 2, $\theta_n = 2n\pi$, and $D_s = \delta_s \pi n^2$. For closest equivalence between the two trajectories, let the first circle radius be equal to the initial spiral radius, ρ_1, and let $\rho_1 = \delta_c = \delta_s$. Under these conditions, it can be shown that $D_c = \delta_c\,[\pi n^2 + (\pi+1)n - 1]$, and therefore, $D_c > D_s$ independent of an equivalent separation distance. A rover executing a concentric circular survey of n circles would need to traverse over $(4n-1)\delta_c$ meters more to cover the same area as it could with a spiral trajectory of n branches. As an example, to traverse a survey trajectory of $n = 3$ concentric circles separated by $\delta_c = 10$ m a rover would drive a linear distance of 397 m; to survey a roughly equivalent area using a spiral trajectory of $n = 3$ branches separated by $\delta_s = 10$ m it would drive a linear distance of 283 m, or 29% less in this case. Computer simulations were used to develop and verify the survey algorithms to be later implemented on a Pioneer 2-AT commercial mobile robot. Fig. 3 depicts 2-D simulated execution of the shorter spiral survey; the target robot platform is also shown in a 3-D simulation using the Webots (http://www.cyberbotics.com) commercial mobile robot simulation software developed by Cyberbotics, Ltd.

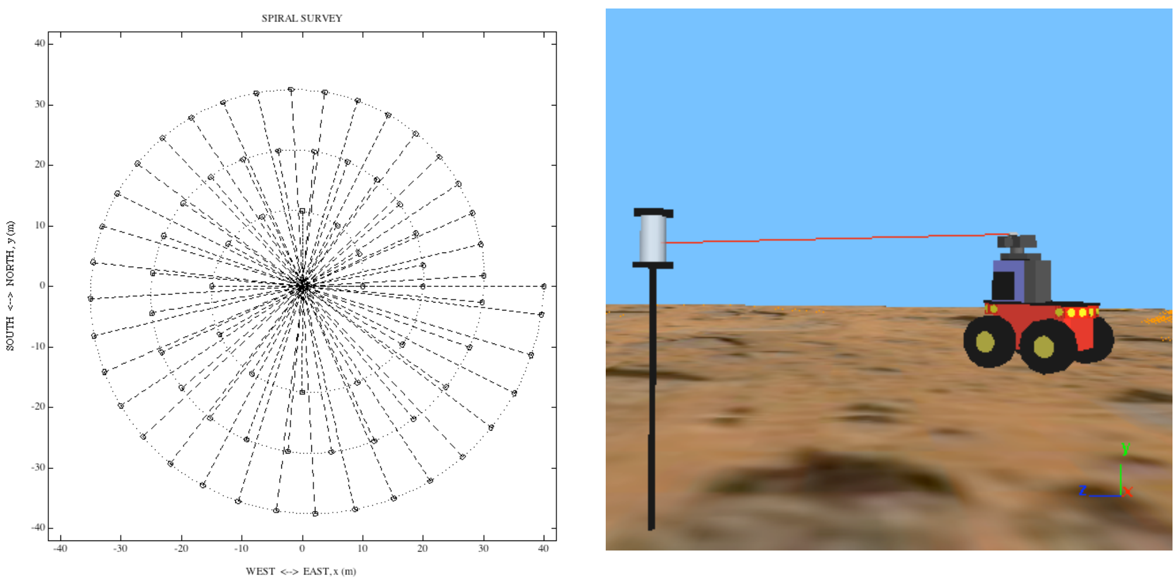

Figure 3. 2-D spiral survey (left) of 3 branches and robot icons at measurement nodes, each with dashed line (diode laser beam) pointed at retroreflector (origin), and related 3-D scene (right).

5. CONCLUSIONS

A new mobile surveying application is introduced involving a remote sensor-based area coverage problem for which we advocate circular and spiral motion trajectories. An overarching goal is to develop smart autonomous mobile instrument systems for in-situ science surveys. Early progress toward that end is presented, namely, algorithms for following both candidate survey trajectories that are appropriate for an open-path distributed spectrometer configuration. The proposed approach offers a wide area coverage solution that obviates the need to traverse the entire survey area by virtue of the remote sensing function of the open-path spectrometer. The concentric circular and spiral survey trajectories will be used to guide an autonomous rover-mounted spectrometer system designed to conduct search and localization of near-surface biogenic gases on Mars. They are also relevant to similar remote sensor-based area coverage tasks associated with planetary, security/defense, energy, and environmental applications including prospecting on the lunar surface, area surveillance or perimeter patrol, localization of toxic/radioactive ground sources, and environmental site characterization and monitoring.

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